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REAL-TIME SNOW SIMULATION MODEL FOR THE MONONGAHELA RIVER BASIN

by

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REAL-TIME SNOW SIMULATION MODEL FOR THE MONONGAHELA RIVER BASIN[1]

Daniel H. Hoggan, John C. Peters, and Werner Loehlein[2]

ABSTRACT: The Pittsburgh District, U.S. Army Corps of Engineers, is responsible for operating two multipurpose reservoirs in the 7384 square mile (19198 square kilometer) Monongahela Basin. A third reservoir, presently under construction, will soon be operating. The real-time forecasting of runoff for operational purposes requires simulation of snow accumulation and snowmelt throughout the Basin during the winter season. This article describes capabilities of SNOSIM, a model being developed for performing such simulation. The application of this model as part of a comprehensive system of water control software, and some initial simulation results are presented.

(KEY TERMS: real-time forecasting; snow simulation; snowmelt modeling; reservoir operation; Monongahela River.)

BASIN AND RESERVOIR SYSTEM CHARACTERISTICS

The Monongahela Basin is situated in the unglaciated Allegheny Plateau and is characterized by rugged, high rolling hills. The Basin is long and narrow with a total length of 144 miles and an average width of 51 miles. Elevations range from about 4800 feet at the southern divide to 710 feet at Pittsburgh (Figure 1).

Two existing reservoirs, Tygart and Youghiogheny, and a reservoir presently being constructed, Stonewall Jackson, comprise a system for which the primary purpose is flood control. The reservoirs are also used to store water for navigation, pollution abatement, and water supply. The winter season flood control capacities for the Tygart, Youghiogheny, and Stonewall Jackson reservoirs are 278,000, 151,000, and 38,550 acre feet, respectively. Flood control reservations for the summer season are somewhat less.

A real-time data collection network for water control is presently based on 52 self-timed data collection platforms (DCP's) that report via satellite telemetry. The DCP's report stages and elevations measured at 33 stream and reservoir sites, air temperature at 11 sites, and precipitation at 28 sites. Precipitation data from an additional 14 sites outside the Basin are used for making estimates of subbasin-average precipitation. The Basin is divided into 40 subbasins for purposes of runoff simulation.

COMPUTER PROGRAM SNOSIM

The SNOSIM program simulates snow accumulation, ripening, and melt processes to determine snowmelt contributions to runoff, and computes rainfall attenuation and lag caused by snow on the ground. Rain that passes through the snowpack is added to snowmelt to obtain "equivalent precipitation," which is treated as being equivalent to rainfall as an input to a rainfall-runoff model (Hoggan, *et al.*, 1986).

SNOSIM is a component of an on-line software system that includes the capability for data acquisition and processing, precipitation analysis, streamflow forecasting, reservoir system analysis, and graphical display of data and simulation results (Pabst and Peters, 1983). A Data Storage System (DSS) provides a means for the storage and retrieval of measured data and simulation results. An interactive executive program facilitates the use of the software system. Alternative future precipitation and temperature scenarios, or alternative operational constraints, can be readily specified with this program.

SNOSIM is unusual in at least two respects: 1) its computational time interval can be made very short (3 hours, for example), and 2) it is designed for shallow snowpacks. Most snowmelt models have been developed for relatively deep snowpacks in mountainous locations, and most compute at longer time intervals. The procedures embodied in the SNOSIM program are those used by the Pittsburgh District, Corps of Engineers, and would be most applicable to shallow to medium depth snowpacks.

DATA REQUIREMENTS

Data requirements for SNOSIM are subbasin averages of maximum and minimum temperatures, snow depths, and precipitation. Aperiodic snow density data can be used for updating computed snow density. In addition to the streamflow and precipitation data available from the network described earlier, daily measurements of temperature (30 stations) and snow depth (50 stations) are available, and aperiodic measurements of snow density are taken at three stations.

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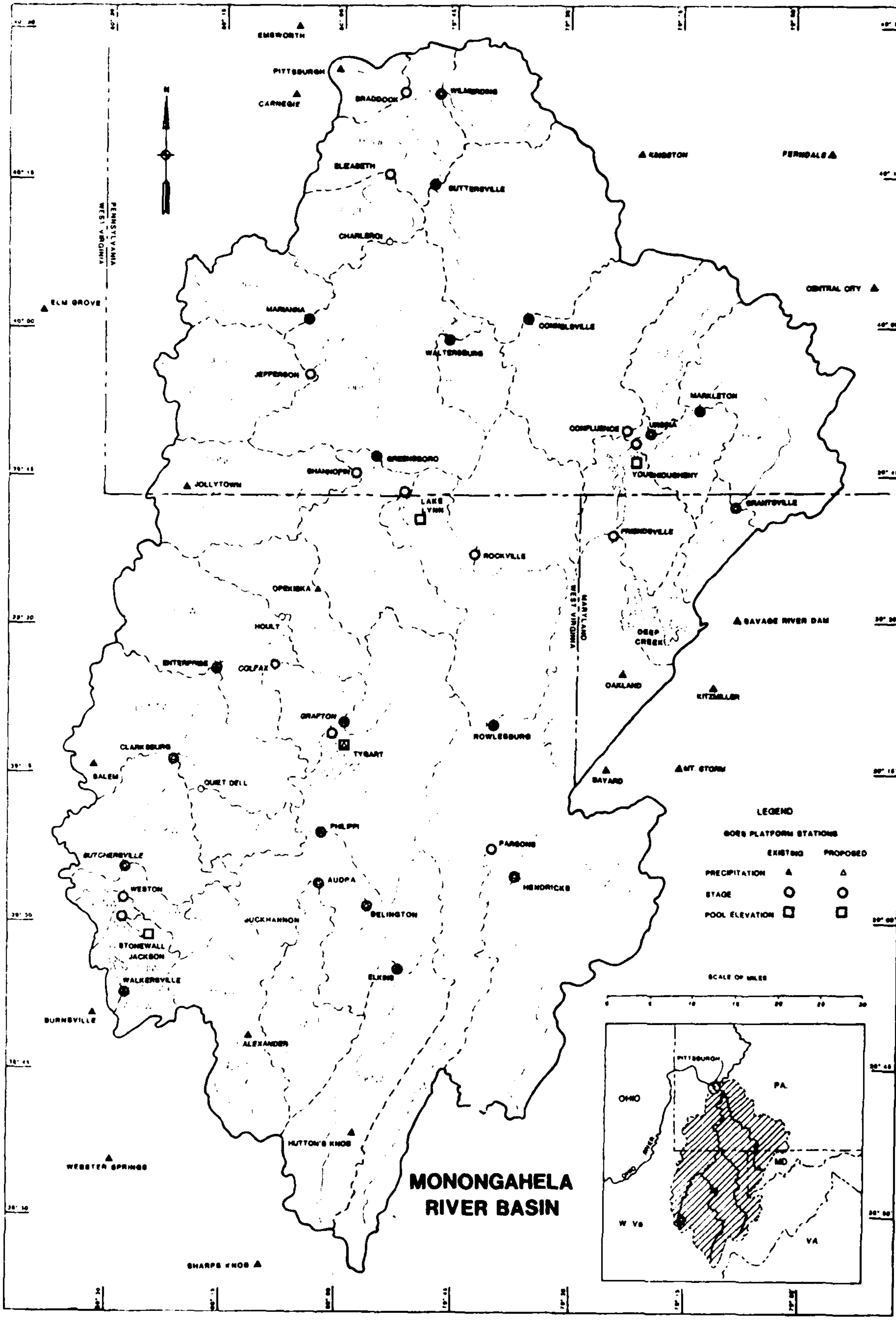

Figure 1. Map of the Monongahela River Basin.

DATA ADJUSTMENTS

Snow depths ordinarily reach a maximum of three to four feet at the highest elevations in the Basin, and all of the snow may melt within a few days from the influence of abnormally high temperatures. The time interval of computations, which may be selected from a range of one to several hours, must be relatively short (e.g., 3 hours) to effectively simulate these conditions. Daily maximum and minimum temperatures are converted to simulation time interval values according to a diurnal temperature distribution used by Pittsburgh District. A linear approximately of temperature distribution between maximum and minimum points is used to simplify computations (Figure 2). Daily snow depths are interpolated linearly to obtain simulation time interval values. Although actual changes in snow depth are not linear, particularly during periods of freezing and thawing, the effect of this assumption on simulation results is minimal because of the small deviation that would occur during a 24-hour period.

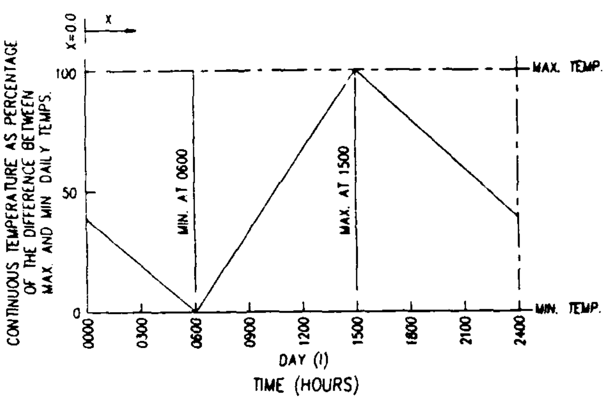

Figure 2. Diurnal Temperature Curve.

Observed snow depths under 20 inches are adjusted upward according to a curve (Figure 3) developed by the Pittsburgh District. For snow depths in this range, the District has found that observed depths based on gage readings are consistently low when compared with the results of snow surveys.

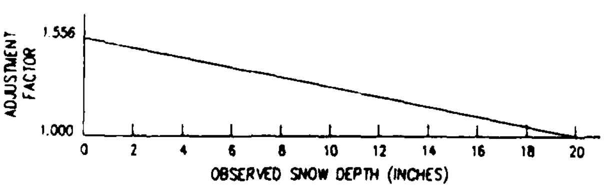

Figure 3. Snow Depth Adjustment Curve.

COMPUTATIONAL LOGIC

Precipitation is divided into rain or snow according to a freezing temperature index. If the average temperature in $^{\circ}F$ is greater than freezing temperature plus 2 degrees, precipitation is computed as rain. Rain, thus obtained, is treated in one of three ways: 1) if there is no snow on the ground, it is added directly to equivalent precipitation; 2) if snowpack exists, but is not ripe (snow density is less than threshold melt density), then the rain is absorbed by the snow; and 3) if the snow is ripe, the rain is lagged before being added to equivalent precipitation.

Snow ripening and melt processes are divided into two stages, from the beginning of the period of simulation until the time of forecast, and from the time of forecast until the end of the period of simulation.

First Stage of Simulation

In the first stage, subbasin averages of observed precipitation, temperature, and snow depth and an initial value of snow density are used to compute a regular time series of water equivalent, snowmelt, and snow density values. This series of computations may be updated with a user assigned value of snow density for any time interval in the simulation.

Tracking of the average snowpack density is essential in the simulation to determine when melt will be triggered. In the model, it is assumed that the average density must reach a threshold density to indicate ripeness before melt will leave the snowpack. Density accounting is accomplished by additions and subtractions to the water equivalent. Precipitation, whether rain or snow, is added; snowmelt and evaporation/sublimation are subtracted.

When snow density is less than the threshold melt density and precipitation occurs, the water equivalent is equal to the water equivalent in the previous time interval plus precipitation.

When there is no precipitation, the water equivalent of the previous period is reduced by a small loss, which includes an evaporation/sublimation loss and any loss from melt and infiltration at the ground surface interface. Evaporation/sublimation from the snowpack is a function of the vapor pressure difference between the snow surface and the air, and wind speed. At middle latitudes during the winter and early spring, the evaporation/sublimation from snow averages less than 0.5 inches per month (U.S. Army Corps of Engineers, 1960). This would amount to about 0.02 inches per day. Loss due to ground melt and infiltration could increase this rate slightly.

If the snow is ripe and the air temperature is above freezing, snowmelt is occurring, and the water equivalent from the previous period is reduced by the amount of melt. Although rainfall also may be occurring, the rain is in transit through the snowpack and does not add to the water equivalent of the snow. The rain is accounted for separately and added to melt later in the process after adjustment for lag. Rain does, however, accelerate snowmelt slightly, so the melt

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rate is increased by an amount proportional to the intensity of the rainfall (U.S. Army Corps of Engineers, 1960).

Combining the rain-melt equation with that for other melt yields an equation for melt during time interval I.

$$M_i = \frac{I}{1440} (C_M + 0.007 R_i)(T_i - T_F) \qquad (1)$$

where:

M_i = snow melt in inches,

I = simulation time interval in minutes,

C_M = coefficient of snowmelt (degree-day factor) in inches of melt per mean daily degree (^{o}F) above freezing,

R_i = observed rainfall in inches,

T_i = air temperature in ^{o}F, and

T_F = freezing temperature in ^{o}F.

Otherwise, if there is no rainfall, the equation is basically the same except that the rain melt factor is eliminated.

After snowmelt has been computed for a time interval, the water equivalent is computed.

Second Stage of Simulation

In the second stage of simulation, which occurs after the time of forecast, predictions of precipitation and temperature are used, and the computations are essentially the same as in the preceding stage except that no snow depths are available. Snow depths are computed in four different ways depending on temperature and snow density conditions.

In the first case, when the snow density is equal to or above the threshold melt density and the air temperature is greater than freezing, melt is occurring and the density can be expected to remain fairly constant. Snow depth under these conditions is computed by dividing the water equivalent in the current time interval by the density in the preceding time interval.

$$S_i = \frac{W_i}{D_{i-1}} \qquad (2)$$

where:

S_i = computed snow depth in inches,

W_i = water equivalent of snowpack in inches of water, and

D_{i-1} = percent snow density expressed as a decimal.

This approach produces a reasonable approximation of snow depth because the density is relatively stable while melt is occurring.

In the second case, when snow density is less than melt density and the air temperature is greater than freezing, the snow depth is reduced slightly by consolidation. Although no melt is occurring in the usual sense of water leaving the snowpack, liquid water from melt occurring at the snow surface is moving to lower levels and increasing snowpack density (Corps of Engineers, 1956). For shallow snowpacks, the reduction in the snow depth under these conditions is directly proportional to the amount of melt occurring at the surface based on air temperature and inversely proportional to the average density of the snowpack.

$$S_i = S_{i-1} - \left(\frac{I}{1440} \cdot \frac{C_M(T_i - T_F)}{D_{i-1}} \right) \qquad (3)$$

In the third case, when the air temperature is below freezing and the snow depth is greater than zero, the snow depth in the current period is equal to snow depth in the previous period reduced by sublimation and increased by snowfall, if any has occurred. The average density of new snow in the United States has been found to be approximately 10 percent (Osborn, *et al.*, 1982), and this value is adopted for computing the depth of new snow.

$$S_i = S_{i-1} - \left(\frac{I}{1440} \cdot \frac{C_s}{(D_{i-1} + \frac{O_i}{0.10})} \right) \qquad (4)$$

where:

C_s = sublimation/evaporation loss in inches per day, and

O_i = observed snow fall in inches of water.

In the fourth case, when the air temperature is less than freezing and there is no snow on the ground for the previous period, the snow depth is equal to any new snowfall that occurs during the period divided by the density of new snow (0.10). The snow density for each time interval during the forecast period is computed by dividing the water equivalent by the snow depth.

The lag of liquid water in transit through the snowpack is computed with a lag factor that has the effect of imposing minutes of lag per inch of snow depth. A study by the U.S. Army Corps of Engineers (1960) indicates 3 to 4 hours of lag for moderate depths of snow. The Pittsburgh District has used 4 to 6 hours of lag for depths ranging up to 2 or 3 feet. Based on this information, 30 minutes of lag per inch of depth is probably reasonable for vertical drainage.

Since most snowmelt originates at the snow surface and travels down through the snowpack, snowmelt as well as rain are adjusted for lag.

In regions of mild to flat slopes, the delay to runoff caused by snowpack may be much longer than for vertical transit of water through the snowpack alone (U.S. Army Corps of Engineers, 1960). Thus, a large lag factor may be needed to simulate runoff in areas of low relief. Although a single (i.e., global) coefficient of lag may be set for all subbasins in the model with program input, larger or smaller lag coefficients for selected subbasins also may be specified.

The lag diminishes with decreasing snow depth; however, for shallow snowpacks that may entirely disappear during the course of a snowmelt event, a counteracting effect may tend to increase the lag of snowmelt as depth decreases. In a subbasin with moderate to high relief, typical of subbasins in the Monongahela River Basin, snow cover recession generally will begin at the mouth of the subbasin and move upstream toward higher and more distant areas. Thus, as the effective center of snowpack mass moves farther away from the mouth, the average travel time for the snowmelt to reach the mouth increases. To compensate to some extent for this effect, the lag for snowmelt, established at the depth when the pack first becomes ripe, is retained until the snow depth diminishes to zero. Rainfall lag, on the other hand, is not affected in this manner and decreases with diminishing depth.

As a final step, after rain and snowmelt are adjusted for lag, lagged amounts of each occurring in the same time interval are added and combined with any other rainfall (which may occur in the case of snow-free time intervals) to produce an equivalent precipitation hyetograph for the entire period of simulation. When there is no snow on the ground, the equivalent precipitation is set equal to the observed rainfall.

INPUT AND OUTPUT

Much of the input required, aside from the climatological data to be processed, is ordinarily generated with the interactive executive program that links SNOSIM with data storage and other software. However, the input can alternatively be entered with a card image input file. The forecast data and time, the starting and ending times of simulation, and the computational time interval are set. Zone-specified future precipitation and maximum and minimum temperature departures from normal may be entered. Five simulation parameters may be set: 1) the coefficient of lag (COEFLG); 2) the freezing temperature (FRZTP); 3) the threshold melt density (RMLTDN); 4) the snowmelt coefficient (SMCOEF); and 5) the sublimation factor (SUBFAC). Snow density data for updating can be specified either zonally or for individual subbasins and by a specified amount or percentage change to existing values.

Since the model has the capability to assign temperature, snow density, and precipitation values by zones, a basin zone file is required, which assigns subbasins to common zones. Departures from normal daily temperatures are used in forecasting, and normal daily temperatures are used to fill in missing data, so a file of normal daily temperatures for each subbasin also is required. This file can be generated from daily normal temperature data for stations with the program PRECIP (U.S. Army Corps of Engineers, 1986), which computes subbasin averages from station data.

Output from the model consists of two tables: a subbasin output table for each subbasin, which lists observed and computed values of key variables for all time intervals in the simulation; and a summary table, which presents totals and other comparative data for all subbasins.

PROCEDURE FOR REAL TIME FORECASTING

The following sequence of operations is performed in a real-time application of SNOSIM.

The computer program PRECIP is used to develop subbasin-average values of precipitation with a 3-hour interval, and of maximum and minimum air temperature, and snow depth, with a daily interval. PRECIP is designed to search for the nearest reporting gages so that missing data does not have to be filled in prior to developing the estimates with spatial and other weighting factors.

SNOSIM is then executed to determine the equivalent precipitation. The information required by the program is automatically retrieved from various files. Such information includes:

a. time parameters that define the starting and ending times for the simulation and the time of forecast;

b. subbasin-average values for precipitation, maximum and minimum daily temperature and snow depth;

c. future precipitation amounts, and future maximum and minimum daily temperatures (in terms of departures from normal);

d. normal daily maximum and minimum temperatures; and

e. snow density data, if available.

The computer program HEC-1F (U.S. Army Corps of Engineers, 1986) is used to calculate discharge hydrographs for each subbasin. Hydrographs are routed and combined throughout the basin to provide forecasted hydrographs of inflow to reservoirs and hydrographs at downstream control points. Observed streamflow data are used wherever it is available in the process of tracking flood wave movement through the stream network. The capability also exists to optimize runoff parameters for gaged headwater subbasins (Peters and Ely, 1985).

Both the discharge hydrographs that are calculated with HEC-1F and the reservoir storages are input to the computer program HEC-5 (U.S. Army Corps of Engineers, 1986) for simulation of the reservoir system and determination of reservoir releases. Releases are determined in accordance with constraints at downstream control points while keeping the system "in balance." A wide variety of factors that affect release decisions can be accommodated, including

channel capacity at downstream control points, emergency conditions requiring prereleases, minimum-flow requirements, etc. Output such as hydrographs of discharge, reservoir stage, and storage are written to the Data Storage System so that they can be readily displayed and analyzed.

Iterations of the above sequence can be made as required to enable the evaluation of alternative future precipitation/temperature conditions or operations constraints.

TEST APPLICATION

A snowmelt flood event in February 1985 was used for testing SNOSIM. A build up of snowpack in mid-February was completely melted by high temperatures in the period of a week, producing high runoff.

The model was first applied to the 15 headwater subbasins in the Monongahela River Basin. No special weighting factors for temperatures or snow depths were used in the computation of subbasin averages from gage data. The program PRECIP has the capability for introducing normalized weights, such as normal maximum and minimum temprratures and normal snow depths. Elevation differences may also be used for weighting temperature data. The purpose of the weighting is to adjust point (gage) values for local variations.

The real-time rainfall-runoff model HEC1-F was run following SNOSIM, using equivalent precipitation computed by SNOSIM as an input to compute hydrographs for all subbasins. A comparison of the computed and the observed hydrographs revealed that the fit was quite good in some subbasins; for example, subbasin MAKP (Figure 4), but the timing of peak discharge was not good in others; for example, subbasin BKNW (Figure 5). Through the introduction of snow depth weighting based upon elevation differences and adjustment of lag factors, a satisfactory fit of hydrographs could be achieved for all subbasins (note the improvement in fit for subbasin BKNW in Figure 6).

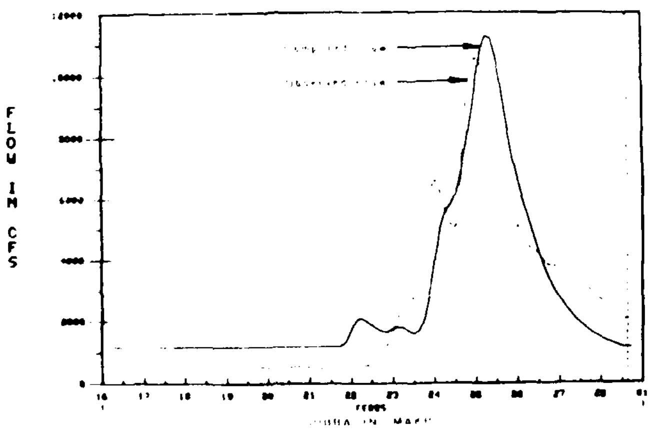

Figure 4. Observed and Computed Flow for Subbasin MAKP.

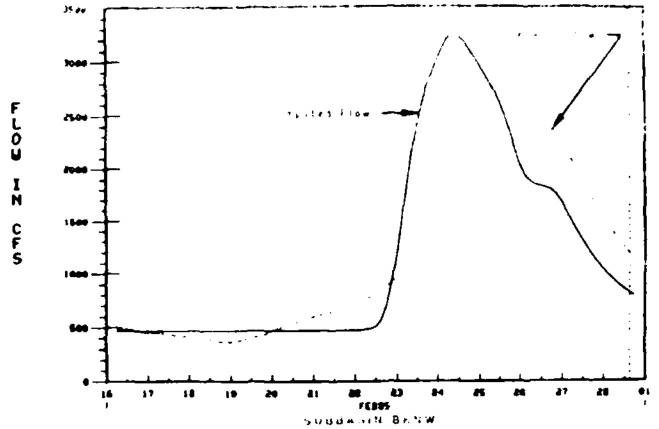

Figure 5. Observed and Computed Flow for Subbasin BKNW.

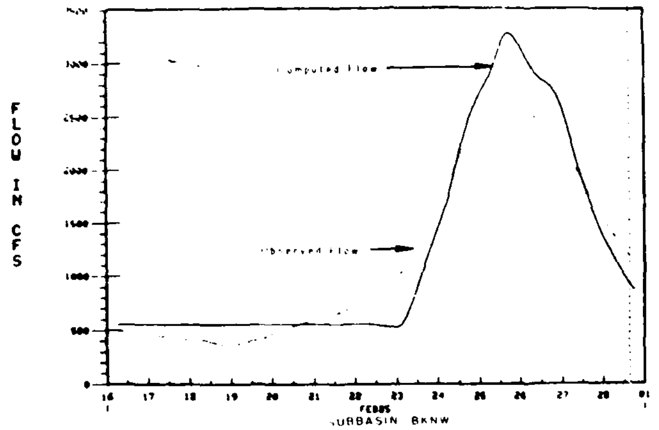

Figure 6. Observed and Computed (with weighting and lag adjustment) Flows for Subbasin BKNW.

One of the key computations in SNOSIM is for the snow depth after the time of forecast, when no observed values are available. Comparison of computed with observed snow depths indicated that the model produced a reasonably good approximation. See the results for subbasin MAKP shown in Figure 7. Because of the lack of significant rainfall in the test event, verification of the rain-on-snow melt simulation in the model was not possible.

CONCLUSIONS

Although snow accumulation and melt processes are highly complex and are influenced by a large number of variables, an attempt was made to keep the level of model sophistication consistent with data availability and operational requirements. Thus, data inputs have been limited to temperature, snow depth, precipitation, and snow density. However,

several parameters and weighting factors can be adjusted by the user to reflect the influence of complex factors that are not included in the model.

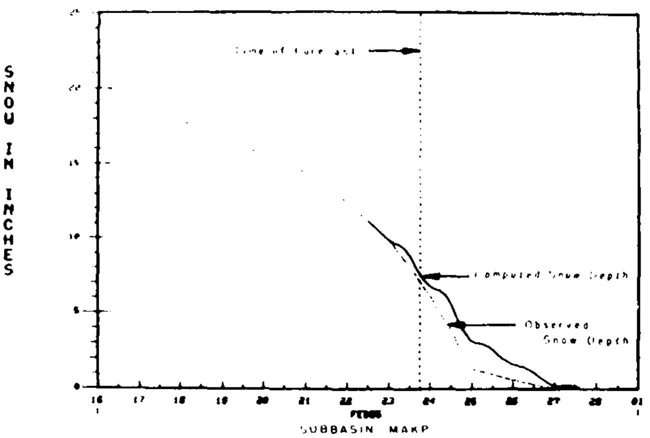

Figure 7. Observed and Computed Snow Depths for Subbasin MAKP.

Testing of the model with data from the February 1985 flood event indicated that obtaining the correct timing of runoff from subbasins is probably the most significant problem to be anticipated. Since different factors or combinations of factors can be employed to influence the timing, the question arises as to what strategy to use. For example, all of the following factors affect timing, so any or all could be considered for adjustment: 1) initial snow density; 2) threshold melt density; 3) freezing temperature (air); 4) snowmelt coefficient; 5) coefficient of lag; 6) temperature weighting factors used in subbasin averaging by program PRECIP; 7) snow depth weighting factors used in subbasin averaging by program PRECIP; and 8) loss rates used by program HEC1-F.

The factors that produce the greatest effect on timing are the weighting factors used in subbasin averaging and the lag factor. In testing the model, lag factors were used almost exclusively to correct timing problems; however, future operation of the model may indicate that more emphasis needs to be given to weighting in the subbasin averaging process. Good spatial averaging of snow depth data measured at stations is particularly difficult to achieve, and further research in this area is needed. Testing of the model with this one event obviously is just a start in the process of developing an effective operational system. Refinement of the model based on experience and data from future events is anticipated.

ACKNOWLEDGMENTS

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19 ABSTRACT (Continue on reverse if necessary and identify by block number)
The Pittsburgh District, U.S. Army Corps of Engineers, is responsible for operating two multipurpose reservoirs in the 7384 square mile (19198 square kilometer) Monongahela Basin. A third reservoir, presently under construction, will soon be operating. The real-time forecasting of runoff for operational purposes requires simulation of snow accumulation and snowmelt throughout the Basin during the winter season. This article describes capabilities of SNOSIM, a model being developed for performing such simulation. The application of this model as part of a comprehensive system of water control software, and some initial simulation results are presented.

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